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APPLICATIONS OF RAYLEIGH SCATTERING TO TURBULENT FLOWS WITH HEA--ETC(U)
MAY 82 L TALBOT, F ROBBEN F49620-80-C-0065
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Rayleigh scattering has been developed as a diagnostic tool and used in conjunction with Laser Doppler velocimetry to study two reacting flows; the interaction of a Karman vortex street with a flame, and the interaction of grid-produced turbulence with a flame. Vortex street interaction is characterized by radical distortion of the flame front. Dilatation effects downstream of the flame front dominate, and vortices are not discernible in this region. Numerical modeling gave qualitatiive agreement with the experimental results. For the grid-induced turbulence, the measured density and velocity statistics were

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compared with the predictions of the Bray-Moss-Libby model. It was found that intermediate states had to be taken into account. Two-point density correlation measurements, the first ever reported, showed that the length scales of turbulence within the reaction zone were the same in all three orthogonal directions. Space-time correlation measurements in the flow direction were in accord with the Taylor hypothesis.

FINAL REPORT

AFOSR Contract #F49620-80-C-0065

APPLICATIONS OF RAYLEIGH SCATTERING TO TURBULENT FLOWS WITH HEAT TRANSFER AND COMBUSTION

The need for an improved understanding of the effect of turbulence on chemically reacting flows has long been recognized. However, the inherent experimental and theoretical difficulties associated with these flows have continued to impede progress towards the development of models which could eventually be used in practical design situations. From an experimental point of view, the difficulty of obtaining flow measurements is attested to by noting that as recently as 1965 a review of experimental data (Williams, 1965) showed that the rms velocity was the only turbulent parameter reported. New measurement techniques, notably laser Doppler velocimetry (LDV) have improved the situation, but the experimental data available is still sparse compared with data for other turbulent flows. The theoretical picture for turbulent flows with combustion is complicated by the necessity of introducing density variations in the theoretical specification of the problem. Numerical models for turbulent flows in which the fluid may be considered incompressible now successfully predict details of fairly complex flows (Reynolds, 1976). However, these models are not easily applied to combustion problems since

the introduction of variable density results in terms which have no counterpart in the incompressible models (Libby and Williams, 1976). A set of conservation equations whose general form is similar to the incompressible time averaged equations results if density weighted time averages are employed. No data exists to indicate whether analogous terms from this set of conservation equations may be modelled using results from incompressible flows as a guide. In order to investigate this possibility correlations of density and velocity need to be measured.

Under previous AFOSR grants feasibility studies indicated Rayleigh scattering to be a reliable and accurate method of determining gas density under typical combustion conditions (Pitz et al., 1976; Cattolica et al., 1977). These Rayleigh diagnostic techniques have been complemented by the development of LDV techniques in both laminar and turbulent flows. In the present work both techniques are applied to the study of the propagation of flame fronts in turbulent flows.

Rayleigh scattering in gases results from the inhomogeneous nature of the medium produced by fluctuations in the dielectric constant. The Rayleigh scattering intensity is related to the gas density as below:

$$I_R = C\, I_o\, N\, \Sigma\, X_i\, \sigma_{Ri} \qquad (1)$$

where I_R is the intensity of Rayleigh scattered light, a

calibration constant of the optics, I_o, the incident laser light intensity, N, the total molecular number density, X_i, the mole fraction of chemical species, and σ_{Ri}, the Rayleigh cross-section for the i^{th} species. Although (1) indicates I_R to be dependent upon the degree of reaction through the species-dependent terms, calculations indicate that for typical combustion conditions, the Rayleigh scattering, to an accuracy of better than 3%, is independent of the change in gas composition and directly proportional to density. This is primarily due to the relatively small differences in σ_{Ri} and the dilute nature of products and fuel components in air-fuel mixtures.

This result has been corroborated by comparing theoretical results with measurements in the laminar boundary layer of a heated flat plate (Schefer et al., 1980) and the successful application of Rayleigh scattering to laminar flows with heat transfer and combustion has led naturally to the initiation of studies of disturbed and turbulent combustion flows.

During the period of the subject AFOSR contract, combined LDV and Rayleigh diagnostic techniques were used to study the following problems.

(1) The interaction of a Kármán vortex street with a flame front;

(2) The interaction of grid-produced turbulence with a flame front.

1. The interaction of a Kármán vortex street with flame front

The interest in this problem derives from the observation that large-scale 'coherent' structures play an important role in determining the characteristics of flame propagation in turbulent flows. The Kármán vortex street provides an idealization of this interaction. The results of this study are reported in Namer (1980) and Namer et al. (1982). They may be summarized as follows:

a) The mean statistical properties of the flame show the development of the turbulent flame brush by the vortex street and the reduction in turbulent intensity behind the flame along with the disappearance of a discernable wake from the turbulence-generating rod. The probability density functions of the density indicate the general validity of a flame sheet model based on the presence of burned and unburned gas, but with significant (~ 30%) contribution of intermediate states. Detailed comparison with some of the theoretical predictions of Bray and Libby (1976) and Bray and Moss (1977) show reasonable agreement but also indicate the necessity of taking intermediate states into account in order to obtain quantitative agreement.

b) By using a phase-locked technique for recording the vortex structure it was possible to obtain complete mapping of the flow field for given positions of the Kármán vortices shed by the rod. Contour plots of constant velocity contours identified the vortex structure. When a flame is present the

vortex structure is distorted and displaced upstream of the flame front, and is not discernable downstream of the flame. The flame front is radically distorted by the vortices as is most clearly evident from the density measurements. As expected from the scale of the 'turbulence' and the Damkohler number, it appears that there is only a single flame front which is distorted, and that pockets of burned and unburned gas are not being generated.

The experimental results were compared with numerical calculations of the flow and flame front due to Karasalo et al. (1980). In these calculations single vortices are inserted into the flow to simulate the Kármán vortex street, and the flame is modelled as a line source of specific volume. There was qualitative agreement between the experiment and the model calculations, but the calculations indicated considerably less perturbation of the flame front than found experimentally.

2. The interaction of grid-produced turbulence with a flame front

An extensive set of measurements on turbulent flame structure in the presence of homogeneous, isotropic grid-generated turbulence have been carried out. The results are reported in Bill et al. (1981), Bill et al. (1982) and Namazian et al. (1982)

In the first set of measurements, LDV data were combined

with Rayleigh data to obtain density and streamwise velocity statistics for a pre-mixed V-shaped ethylene/air flame. Turbulent flame propagation was studied for three upstream flow velocities, U = 2.45, 5.0 and 6.84 m/s, with equivalence ratios ranging from 0.55 to 0.75. The angle of the flame with the flow axis was varied from 12° to 24°. Profiles of the mean values and fluctuation intensities of velocity and density were obtained through the flame. For all conditions, the velocity fluctuation intensity was observed to decrease behind the flame, indicating the dominance of dilatation effects. Additionally, the profiles of the mean streamwise velocity component indicated that the flow was significantly deflected at the flame front, particularly for the case of the most oblique (12°) flame. In this flame condition the wake of the flameholder was found to dominate the flowfield behind the flame and vortices were observed in the burned gas. Thus the results for this flame configuration were not typical of the interaction of a flame with grid-produced turbulence. Probability density functions of the Rayleigh-scattered radiation and measured turbulence intensities indicated that states intermediate between the unburned and burned gases are likely to be significant in determining density statistics.

In the second set of measurements a more detailed comparison is made between the Rayleigh scattering results for the density statistics in a premixed V-shaped flame and the predictions of the Bray-Moss-Libby model. Probability density distributions

of density fluctuations are obtained at a number of locations through the flame. A comparison of these results with the predictions of the B-M-L model, in which intermediate states are neglected, shows that this neglect is not justified for the conditions of the experiment. However, the measured skewness of the density fluctuations is accurately predicted by the model. The data suggest that it should be possible with relatively modest modifications in the model to obtain satisfactory agreement between theory and experiment.

In the most recent set of measurements on V-shaped flames propagating into grid-produced turbulent flow, two-point correlations of density have been obtained. These results represent an entirely new advance in the diagnostics of turbulent flows. Since they have not yet been published, we report them in detail.

A unique beam splitter plus split-lens optical system was employed to produce two laser beams whose waist locations could be varied in a continuous manner from coincidence to any arbitrary distance apart (limited only by the diameter of the optics). Separate photomultipliers focused on the waists of each of the beam simultaneously recorded the Rayleigh scattering at the waist locations. These signals were sampled at a 10 kHz rate with a PDP-11/10 computer and stored on magnetic tape for post-processing. The flow system is shown in Figure 1 and the optical system is shown in Figure 2.

The two point correlation function $R(\delta)$ is defined by

$$R(\delta) = \frac{\langle\rho_1'(t)\rho_2'(t)\rangle}{\langle\rho_1'(t)^2\rangle^{1/2}\langle\rho_2'(t)^2\rangle^{1/2}}$$

where δ is the distance of separation of the measurement positions denoted by subscripts 1 and 2, and ρ' is the density fluctuation and <> denotes the time average. Measurements of $R(\delta)$ were made through the flame with δ taken in each of the three coordinate directions, x, y, z (Figure 1). The results are shown in Figure 3. It is seen that the values of the spatial correlations are very similar in the three directions, indicating that the spatial structure of the turbulent flame, under the conditions of the experiment, is such that the associated integral scales are the same in these directions. The integral scale, represented by the area under the $R(\delta)$ curve, is found to be approximately 2 mm, about half the thickness of the turbulent flame zone. Interestingly, the transverse integral scale of the grid turbulence was also about 2 mm.

The space-time correlation, defined by

$$R(\delta,\tau) = \frac{\langle\rho_1'(t)\ \rho_2'(t+\tau)\rangle}{\langle\rho_1'(t)^2\rangle^{1/2}\langle\rho_2'(t)^2\rangle^{1/2}}$$

where τ is the time delay, was also evaluated, and is shown in Figure 4, as a function of τ for several values of δ taken

along the x or flow direction. The maxima in each curve is proportional to δ, with the proportionality factor about 7 m/s, which was the flow velocity. Since previous measurements have indicated that for the conditions of the experiment the axial velocity does not change significantly through the flame, this indicates that the turbulent density structures are simply convected downstream by the flow, as is suggested by the Taylor hypothesis.

In Figure 5 the maximum value of $R(\delta,\tau)$ is plotted as a function of δ. The decrease of $R(\delta,\tau)$ with δ implies that the turbulent density structures decay as they are convected by the flow. Figure 6 shows $R(\delta,\tau)$ for δ taken in the transverse direction within the flame. In this case the maximum is always found at $\tau = 0$.

All of these results should be of use in improved modelling of turbulent flows with combustion.

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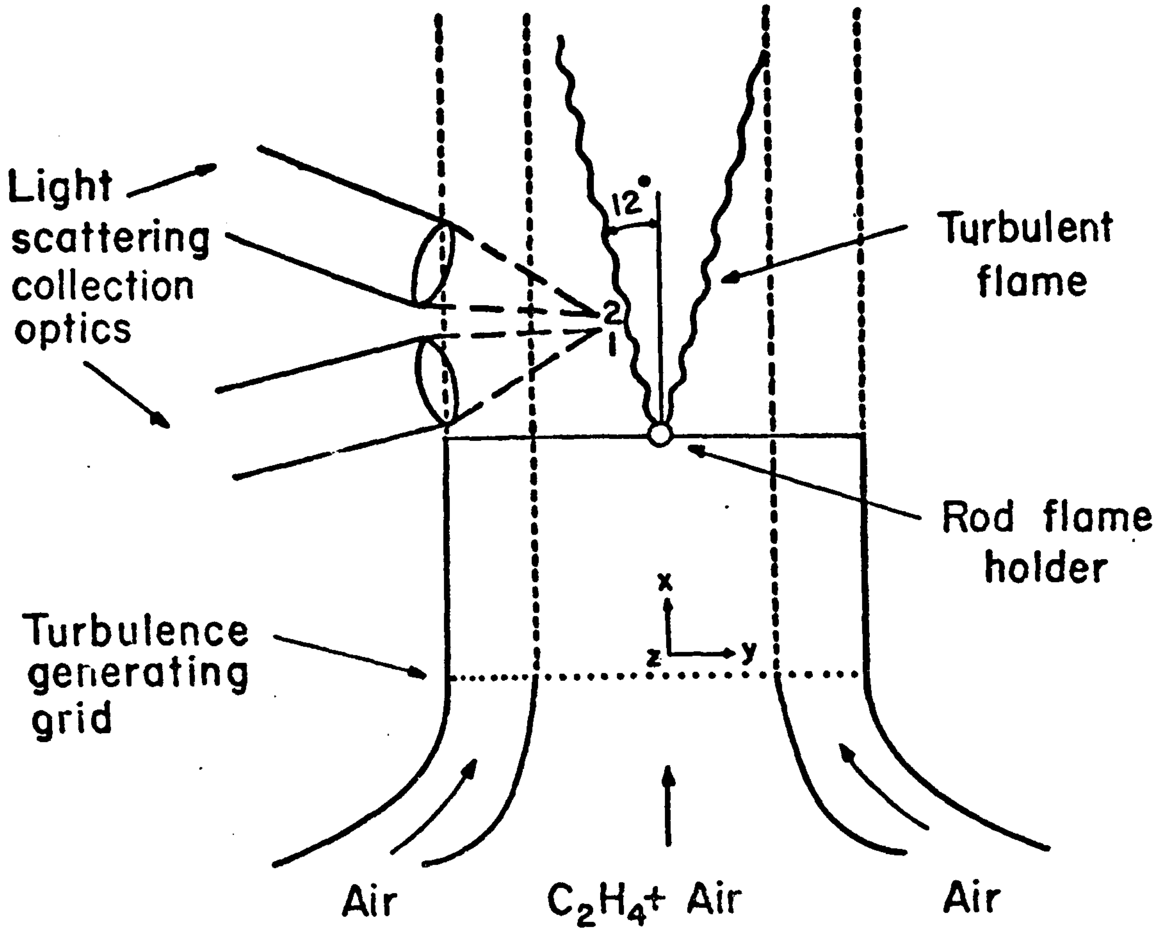

FIG. 1. SCHEMATIC OF THE EXPERIMENTAL APPARATUS FOR TWO POINT RAYLEIGH SCATTERING MEASUREMENTS.

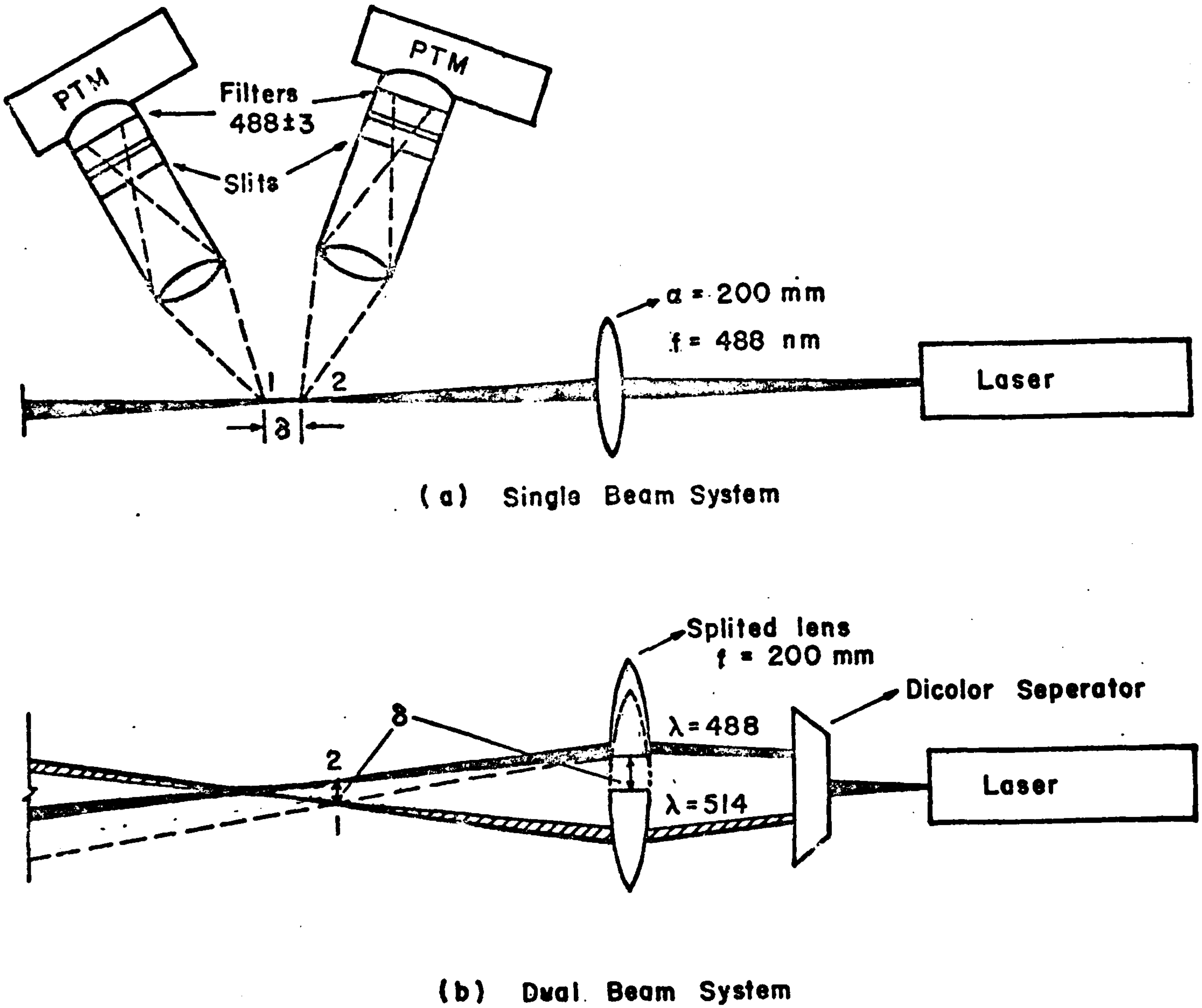

FIG. 2. THE OPTICAL SET-UP FOR TWO POINT RAYLEIGH SCATTERING TECHNIQUE. SINGLE BEAM SYSTEM PROVIDES SEPARATION BETWEEN POINTS IN HORIZONTAL DIRECTION AND DUAL BEAM SYSTEM IN VERTICAL DIRECTION.

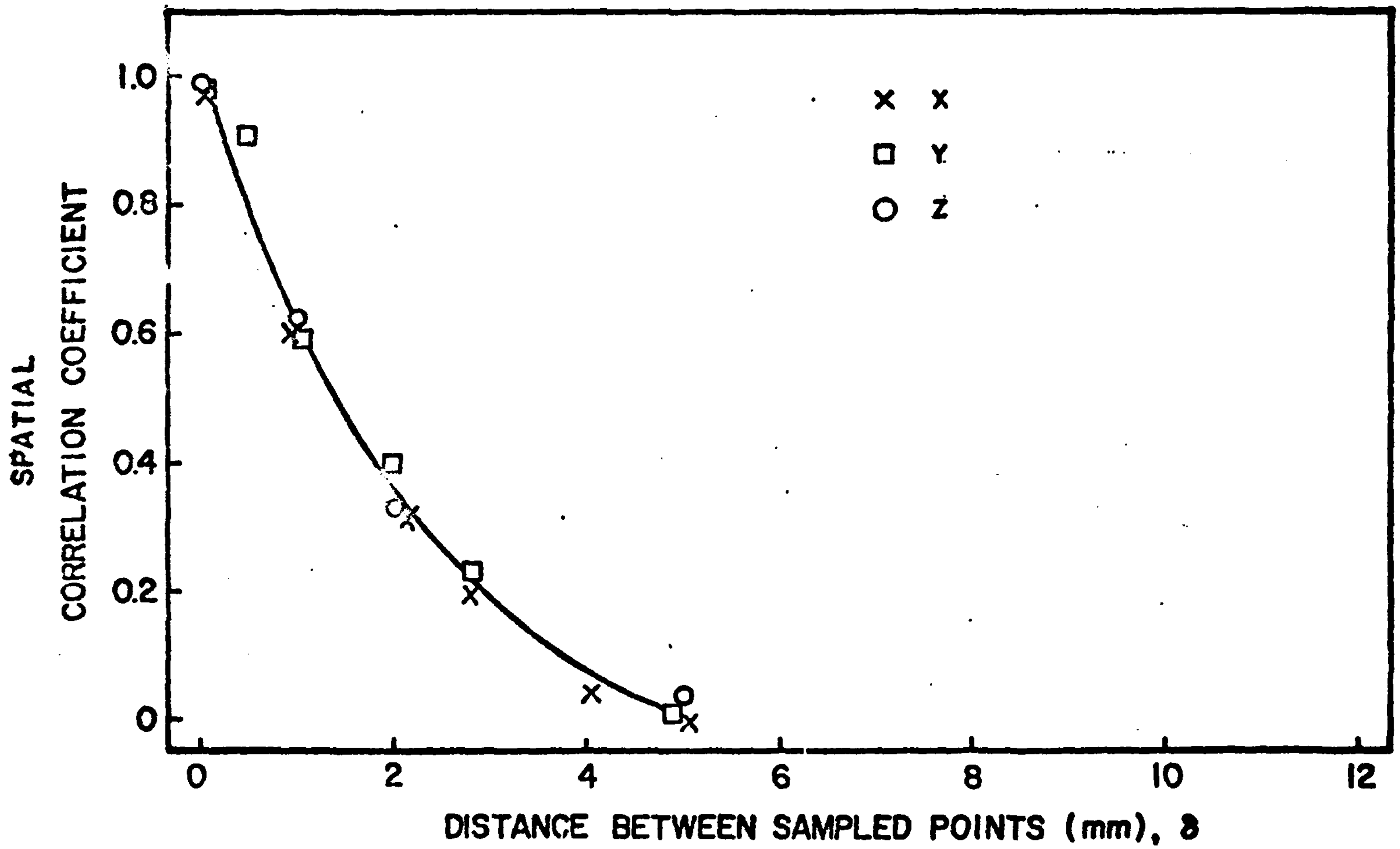

FIG. 3. THE DENSITY SPATIAL CORRELATION IN A TURBULENT FLAME IN THREE ORTHOGONAL X, Y, AND Z DIRECTIONS. MEASUREMENT POINT 35 MM DOWNSTREAM FROM THE FLAME HOLDER.

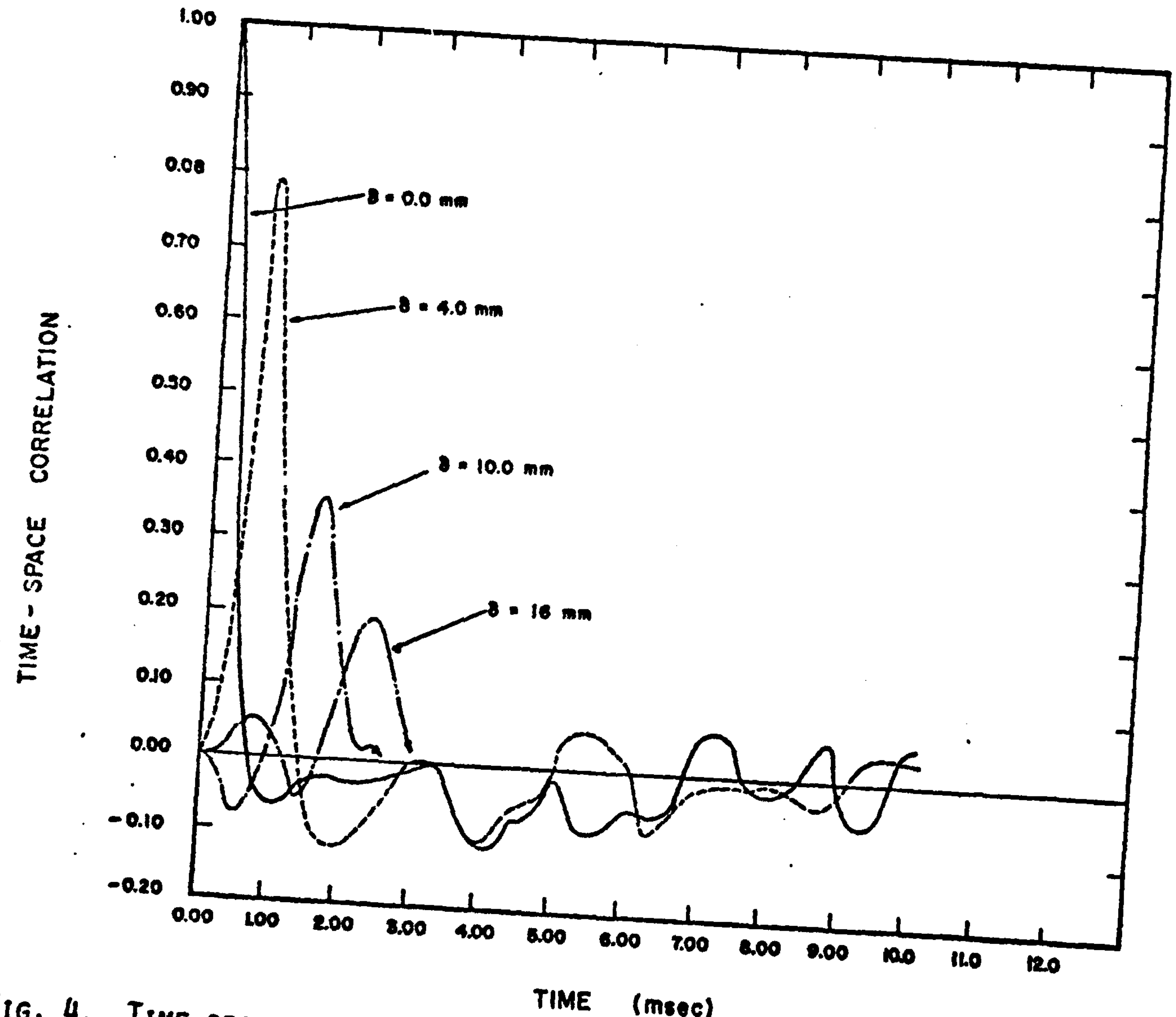

FIG. 4. TIME-SPACE CORRELATION VERSUS THE DELAY TIME FOR SEPARATION OF δ IN THE VERTICAL DIRECTION.

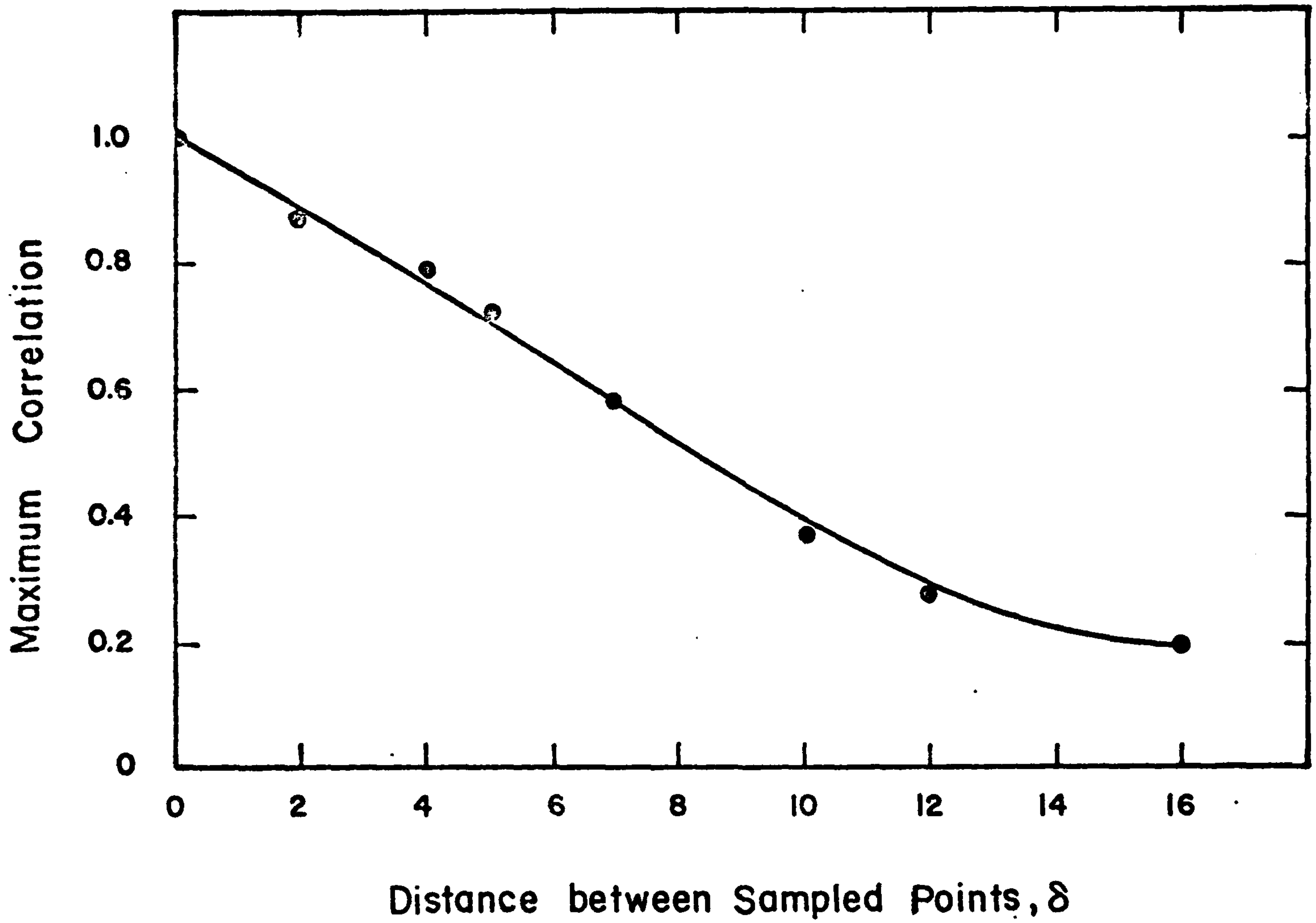

FIG. 5. MAXIMUM VALUE OF THE TIME-SPACE CORRELATION CURVES OF FIG. 4 AS A FUNCTION OF δ, THE DISTANCE BETWEEN SAMPLED POINTS.

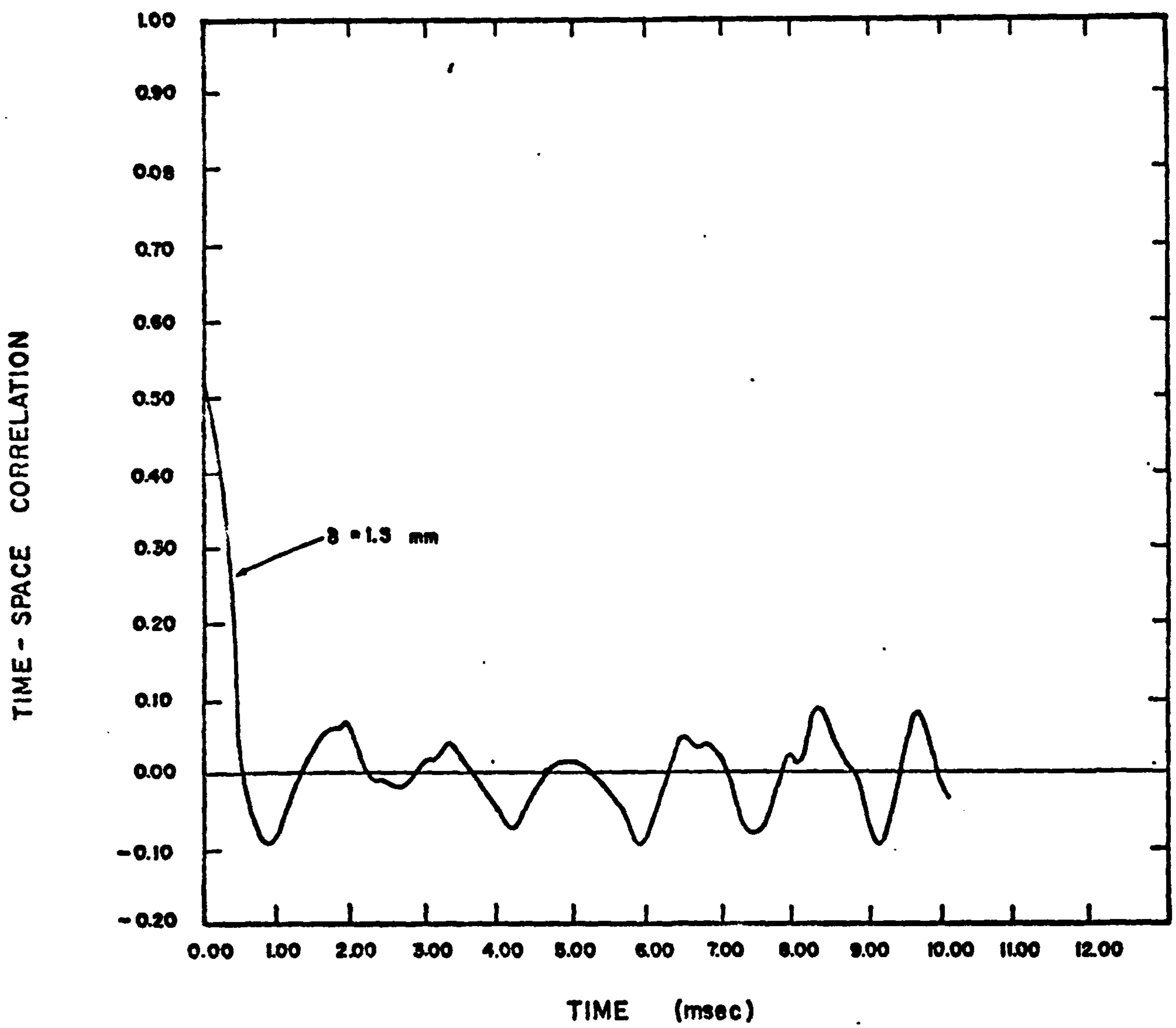

FIG. 6. TIME-SPACE CORRELATION VERSUS THE DELAY TIME FOR SEPARATION δ IN Y DIRECTION.